

PDFs for the LHC

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The PDF4LHC group has benchmarked six modern PDF sets and used them to make predictions for W,Z production and Higgs production at the LHC. The reasons why predictions differ are examined and recent updates to the PDFs and their predictions are presented.

1 Introduction

The PDF4LHC group have benchmarked modern PDF sets from the groups; ABKM, CTEQ, GJR, HERAPDF, NNPDF, MSTW in terms of the predictions for basic LHC cross-sections [1]. Fig 1 shows the comparison of predictions for the W^+ cross section at 7 TeV. The PDF4LHC recommendation [2] is to use the envelope of the MSTW2008, CTEQ6.6 and NNPDF2.0 predictions and add the uncertainty due to $\alpha_s(M_Z)$ in quadrature. However, as can be seen from the figure, this may not be sufficient to cover PDF uncertainties.

There are several reasons why the PDF predictions differ: firstly they are based on different data sets. For example, all the 2010 PDF analyses illustrated, bar the HERAPDF1.0 and the NNPDF2.0, do not use the recently combined inclusive cross section data from HERA-I [3] which are up to three times more accurate than the separate H1 and ZEUS data sets used by previous PDF analyses. These combined HERA data are also shifted in normalisation by $\sim 3\%$ with respect to the previous HERA data, and this partly explains the higher cross section of the HERAPDF wrt CTEQ and MSTW. Secondly, PDFs use different central values of $\alpha_s(M_Z)$, the effect of this is illustrated on the figure. Some groups (HERAPDF, CTEQ, NNPDF) adopt a central value of $\alpha_s(M_Z)$ inspired by the PDG value and others (ABKM, GJR, MSTW) fit $\alpha_s(M_Z)$ simultaneously with the PDF parameters and use their best fit value. Thirdly, the PDF analyses differ in the schemes used to account for heavy quark production. For example, the NNPDF2.0 used a zero-mass variable-flavour number scheme (ZMVFN) and this explains why the NNPDF2.0 predictions lie lower than CTEQ, MSTW, HERAPDF all of which use general mass variable flavour number schemes (GMVFNs). The value of the charm and beauty masses also differ between the PDF analyses. Lastly, PDFs differ regarding choices of PDF parametrisation and theoretical/model prejudices which are imposed. Whereas this latter source of difference represents legitimate, irreducible differences in approach it may be possible to achieve greater concordance on the first three reasons for PDF differences.

2 Heavy Quark Schemes

Let us first consider heavy quark production. The ABKM and GJR groups use Fixed Flavour Number (FFN) treatments, HERAPDF, CTEQ and MSTW use GMVFN and NNPDF2.0 used ZMVFN. However even within GMVFN schemes there is not complete agreement. Predictions

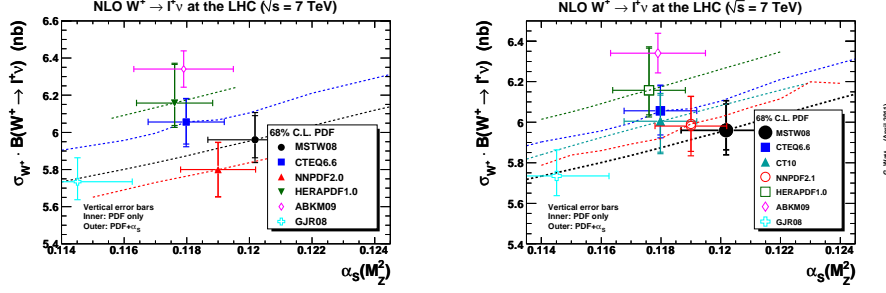


Figure 1: Predictions for the $W+$ cross section at the LHC at 7 TeV from various modern PDF sets as a function of $\alpha_s(M_Z)$. The cross section for each PDF set is shown at the value of $\alpha_s(M_Z)$ used by that group. The vertical error bars represent the 68% uncertainty on the predictions, the horizontal error bars represent the 68% uncertainty on $\alpha_s(M_Z)$ considered by each group. The right hand plot shows the predictions for PDF sets available in April 2010, the left hand side shows the updates from CT10 and NNPDF2.1 available for April 2011. Plots from G.Watt <http://projects.hepforge.org/mstwpdf/pdf4lhc/2010/>

for F_2^c differ between schemes [4] and the choice of scale within a scheme affects predictions. The value of the charm mass can also affect predictions, HERAPDF, NNPDF and MSTW now provide PDFs at different charm mass values so that the effect of this can be evaluated. H1 and ZEUS have recently combined their data on $F_2^{c\bar{c}}$ [5], and these data can help to reduce the uncertainty on PDFs coming from the choice of scheme and the value of the charm mass. These data have been input to the HERAPDF fit together with the inclusive data which were used for HERAPDF1.0. The χ^2 of this fit is sensitive to the value of the charm quark mass. Fig. 2 compares the χ^2 , as a function of this mass, for a fit which includes these data (top right) to that for the HERAPDF1.0 fit (top left). However, it would be premature to conclude that the data can be used to determine the charm pole-mass. The HERAPDF formalism uses the Thorne-Roberts (RT) variable-flavour-number (VFN) scheme for heavy quarks. This scheme is not unique, specific choices are made for threshold behaviour. In Fig. 2 (bottom left) the χ^2 profiles for the standard and the optimized versions (optimized for smooth threshold behaviour [6]) of this scheme are compared. The same figure also compares the alternative ACOT VFN schemes and the Zero-Mass VFN scheme. Each of these schemes favours a different value for the charm quark mass, and the fit to the data is equally good for all the heavy-quark-mass schemes excepting the zero-mass scheme. Each of these schemes can also be used to predict W and Z production for the LHC and their predictions for W^+ are shown in Fig. 2 as a function of the charm quark mass (bottom right). If a particular value of the charm mass is chosen then the spread of predictions is as large as $\sim 7\%$. However this spread is considerably reduced $\sim 1\%$ if each heavy quark scheme is used at its own favoured value of the charm quark-mass. Further details of this study are given in ref. [7].

A further relevant question is what is the charm mass which is being used in the calculations? Is it the pole mass or the running mass? The running mass is independently measured and the ABM group have considered using this mass in their FFN calculations [8]. They obtain a value of $m_c(m_c) = 1.18 \pm 0.06$ GeV in agreement with the PDG value. This should be improved after the input of the combined HERA charm data.

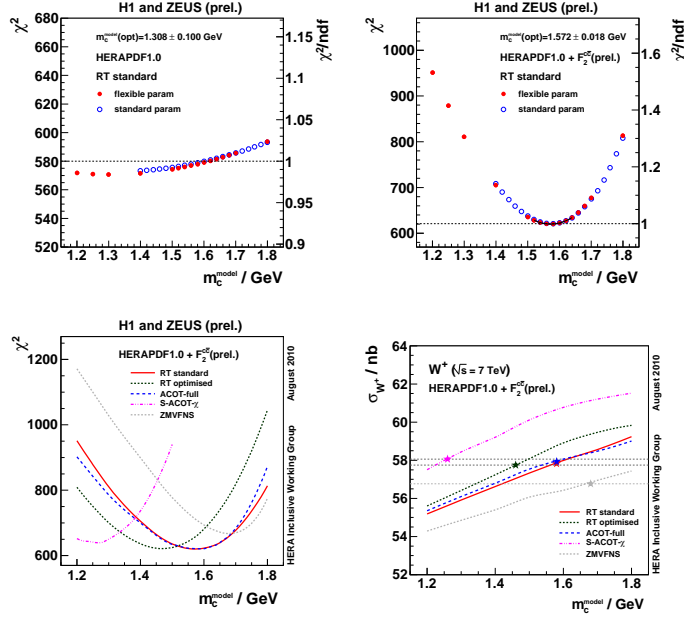


Figure 2: The χ^2 of the HERAPDF fit as a function of the charm mass parameter m_c^{model} . Top left; using the RT-standard heavy-quark-mass scheme, when only inclusive DIS data are included in the fit. Top right; using the RT-standard heavy-quark-mass scheme, when the data for $F_2^{c\bar{c}}$ are also included in the fit. Bottom left; using various heavy-quark-mass schemes, when the data for $F_2^{c\bar{c}}$ are also included in the fit. Bottom right: predictions for the W^+ cross-sections at the LHC, as a function of the charm mass parameter m_c^{model} , for various heavy-quark-mass schemes.

3 2011 updates

There have been recent updates to the PDFs which address some of the issues we have raised. NNPDF2.1 [4] updates NNPDF2.0 to use a GMVFN. CT10 [9] is an update of CTEQ6.6 which includes the combined HERA data in addition to giving special consideration to the Tevatron W asymmetry data (CT10W). ABM11 [10] is an update of ABKM which includes the combined HERA data. HERAPDF1.0 has been updated to HERAPDF1.5 [11] by including further preliminary combined data from HERA-II running. Preliminary H1 data on NC and CC e^+p and e^-p inclusive cross-sections and published ZEUS data on NC and CC e^-p and CC e^+p data, from HERA-II running, have been combined with the HERA-I data to yield an inclusive data set with improved accuracy at high Q^2 and high x [12]. This new data set is used as the sole input to a PDF fit called HERAPDF1.5 which uses the same formalism and assumptions as the HERAPDF1.0 fit. Fig. 3 (left) shows the combined data for NC $e^\pm p$ cross-sections with the HERAPDF1.5 fit superimposed. The parton distribution functions from HERAPDF1.0 and HERAPDF1.5 are compared in Fig. 3 (right). The improvement in precision at high x is clearly visible.

Fig. 1, right hand side, shows the predictions for the W^+ cross section at the LHC at 7 TeV updated to show the predictions of the new PDFs from CT10 and NNPDF2.1. The CT10 and CTEQ6.6 predictions are very similar and the HERAPDF1.5 (not shown) and HERAPDF1.0 predictions are very similar. The NNPDF2.1 prediction has moved up significantly because of the use of the GMVFN scheme. The early LHC data agree well with all the predictions.

It is also interesting to look at the predictions for the ratios of cross sections $Z/(W^+ + W^-)$ and W^-/W^+ . Fig. 4 shows 2010 and updated 2011 predictions. The Z/W ratio is very consistently predicted because flavour dependence almost cancels in the ratio, but the W^+/W^- ratio predictions are quite discrepant - this measures a difference in the u and d

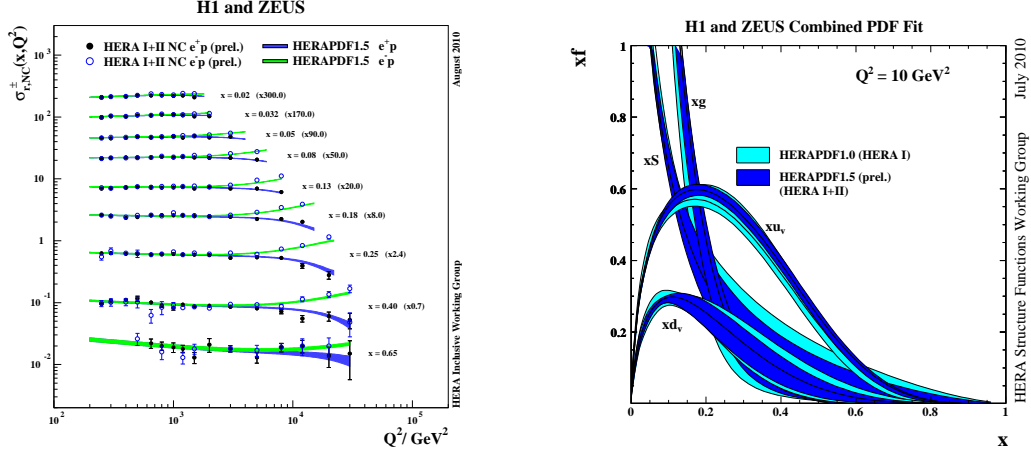


Figure 3: Left: HERA combined data points for the NC $e^\pm p$ cross-sections as a function of Q^2 in bins of x , for data from the HERA-I and II run periods. The HERAPDF1.5 fit to these data is also shown on the plot. Right: Parton distribution functions from HERAPDF1.0 and HERAPDF1.5; xu_v , xd_v , $xS = 2x(\bar{U} + \bar{D})$ and xg at $Q^2 = 10 \text{ GeV}^2$.

valence distributions in a previously unmeasured region of x . The early LHC data are not yet discriminating.

Another way to compare PDF predictions is to look at parton-parton luminosities. Fig. 5 shows the 2010 and 2011 $q - \bar{q}$ and $g - g$ luminosity plots. The 2011 comparisons are in considerably better agreement.

4 The value of $\alpha_s(M_Z)$

All groups bar GJR use values $\sim 0.118 - 0.120$ at NLO but there is a definite low(0.113)-high(0.117) split at NNLO. MSTW obtain the highest value at both NLO and NNLO and this has been attributed to the use of Tevatron jet data in their fits. However, ABM have tried inputting these data and find this has only a small effect on their $\alpha_s(M_Z)$ extraction [10]. There is also a 'folk-lore' that DIS data prefer lower values of α_s however both MSTW [13] and NNPDF [14] have performed DIS only fits in which they find that only the BCDMS data prefer low α_s values. The HERA data actually prefer quite high values. This year we have heard from HERA themselves [15]. HERA have input jet data from H1 and ZEUS in addition to the HERA inclusive DIS data to obtain the HERAPDF1.6 fit. This fit also extends the HERAPDF1.5 parametrisation to use 14 free parameters (this fit is called HERAPDF1.5f)- a term is added such that the gluon may become negative at low x, Q^2 if required (though it does not do so in the kinematic region where data is fitted) and the low- x valence shape of the d-quark is freed from that of the u-quark. When α_s is freed a value of $\alpha_s(M_Z) = 0.1202 \pm 0.0019$ is obtained (where the error excludes the scale errors). This fit also has a harder high- x gluon density (and corresponding lower low- x gluon density) than the HERAPDF1.5 fit, which brings the gluon-gluon luminosity plot for HERAPDF1.6 into closer agreement with MSTW2008. Fig. 6 shows the χ^2 profile of HERAPDF fits with free α_s , with and without the jet data, from which we can appreciate that α_s can only be determined with the addition of jet data. This figure also shows the PDFs from HERAPDF1.6 free $\alpha_s(M_Z)$ and the $q - \bar{q}$ and $g - g$ luminosity plots for the HERAPDF NLO updates of 2011.

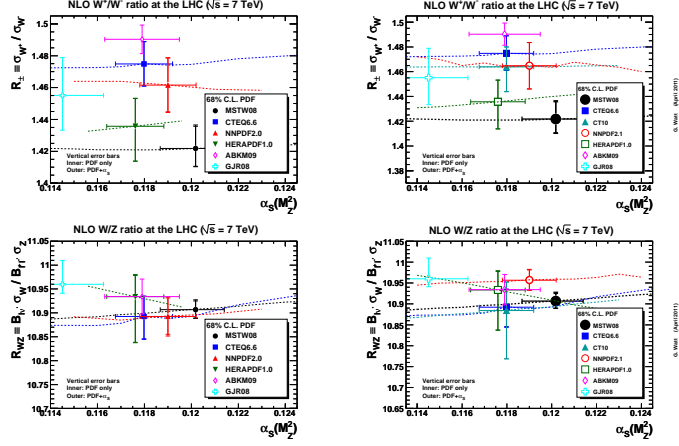


Figure 4: Upper plots: the ratio of W^+ and W^- cross sections at the LHC for the PDFs considered by the PDF4LHC group. Lower plots: the ratio of Z to $W^+ + W^-$ cross sections at the LHC for the PDFs considered by the PDF4LHC group. Left-hand side April 2010, right-hand side April 2011. Plots from G.Watt <http://projects.hepforge.org/mstwpdf/pdf4lhc/2010/>

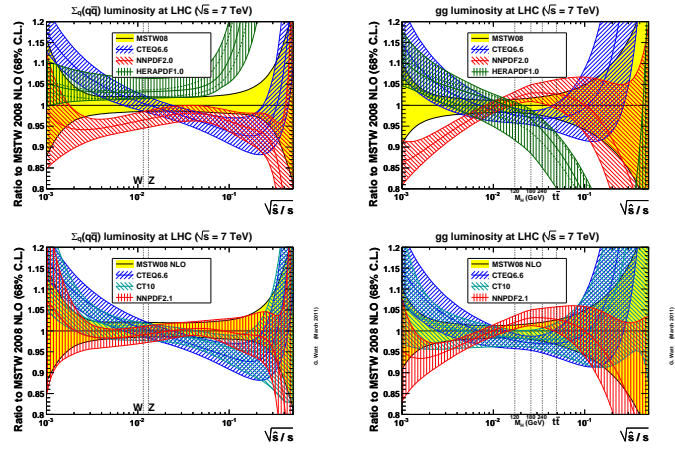


Figure 5: Left hand side: the $q - \bar{q}$ luminosity in ratio to that of MSTW2008 for various PDFs. Right hand side: the same for the $g - g$ luminosities. Upper row, PDFs 2010: bottom row, updates for CT10 and NNPDF2.1 2011. Plots from G.Watt <http://projects.hepforge.org/mstwpdf/pdf4lhc/2010/>

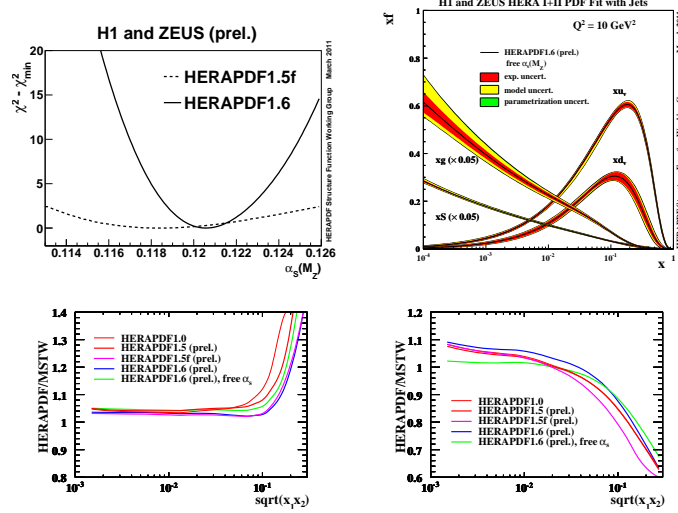


Figure 6: Top left: χ^2 scan vs $\alpha_s(M_Z)$ for the HERAPDF1.5f fit without jet data and for the HERAPDF1.6 fit which uses HERA jet data. Top right the PDFs resulting from the HERAPDF1.6 fit with free $\alpha_s(M_Z)$. Bottom row the $q - \bar{q}$ (left) and $g - g$ (right) luminosities in ratio to MSTW2008 for the 2011 HERAPDF updates and for HERAPDF1.0.

5 NNLO PDFs and predictions for the Higgs

The Higgs cross section is very sensitive to the value of $\alpha_s(M_Z)$ and the gluon-gluon luminosity. For Higgs predictions it is also necessary to consider NNLO calculations. Until this year there were only a few NNLO PDFs [16]. The PDF4LHC recommendation concentrated on the MSTW2008 PDF because it is a global fit. However the predictions of the JR, ABKM and HERAPDF1.0 NNLO PDFs all lie to the low side of MSTW2008 and this was used [17] to cast doubt on the Higgs exclusion limits from the Tevatron which were based on MSTW. Two further issues have arisen related to this. Firstly, Accardi et al [18] have reconsidered deuterium corrections for the fixed target data. They find much larger corrections than have usually been accounted for, and this results in greater uncertainty in the high- x d -quark which feeds into the high- x gluon PDF when it is determined from Tevatron jet data where the $d - g$ process provides a substantial part of the cross section. Secondly, ABM [19] have examined the use of NMC data in the global fits. The NMC data on F_2 have often been used for the PDF fits rather than the cross section data. However, the extraction of F_2 relies on assumptions on the value of F_L which may not be consistent with modern QCD calculations. ABM find that using F_2 rather than the cross section raises their extracted values of α_s erroneously. However both MSTW[20] and NNPDF[21] have repeated this analysis and do not agree with these conclusions (at the time of writing this is still not resolved).

Since the gluon PDF is so important for the Higgs predictions another issue which has been raised is the goodness of fit of the ABKM and HERAPDFs to the Tevatron jet data. Watt and Thorne [20] obtain poor χ^2 for these data when fitting to the HERAPDF1.0, 1.5 and the ABKM09 PDF predictions. However these fits only compare to the central predictions of the HERAPDF and ABKM PDFs. A more valid comparison would account for the PDF error bands. HERAPDF have input the Tevatron jet data to their fit and they obtain much better χ^2 ($\chi^2/ndp = 1.48$ for CDF and 1.35 for $D0$ jets). Significantly the resulting PDFs do not lie outside the HERAPDF1.5 error bands (although they do imply a harder high- x gluon on the upper edge of the error band). ABKM have also made their own fits obtaining $\chi^2/ndp = 0.94$

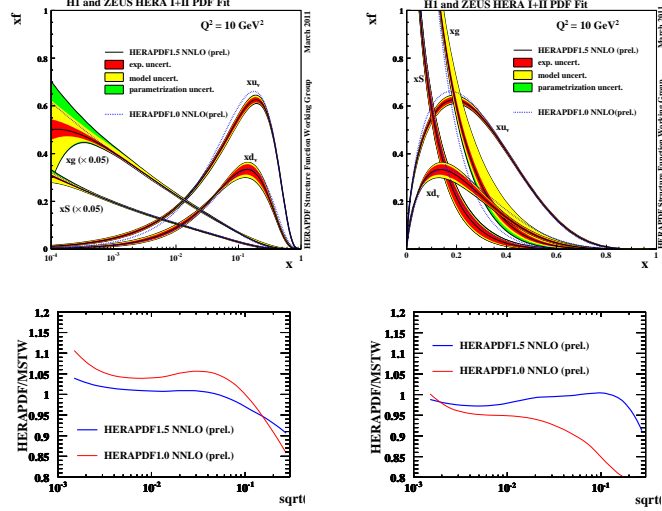


Figure 7: Top row: HERAPDF1.5 NNLO PDFs compared to HERAPDF1.0 NNLO PDFs on log and linear x scales. Bottom row: $q - \bar{q}$ and $g - g$ luminosity plots for HERAPDF1.5 and 1.0 NNLO in ratio to MSTW2008 NNLO.

for D0 di-jet data.

In 2011 many more NNLO PDFs are becoming available. NNPDF presented a preliminary NNLO analysis called NNPDF2.5 (which will be called NNPDF2.1 NNLO) and HERAPDF presented a new NNLO extraction HERAPDF1.5 NNLO [22], with full accounting for experimental, model and parametrisation uncertainties, using the extended form of their parametrisation. An NNLO PDF set from the CT group is also expected soon. Scale differences in NNLO heavy quark calculations are significantly reduced such that NNLO predictions should be in better agreement regardless of the choices made for these schemes. Fig. 7 compares the HERAPDF1.5 NNLO with the preliminary HERAPDF1.0 NNLO which was issued only as central predictions for two values of α_s . The HERAPDF1.5 NNLO fit has a harder high- x gluon. The figure also shows the $q - \bar{q}$ and $g - g$ HERAPDF NNLO luminosities in ratio to MSTW2008, illustrating much closer agreement with MSTW2008 for HERAPDF1.5 than for HERAPDF1.0. This, added to the fact that HERAPDF now recommend that a central value of $\alpha_s(M_Z) = 0.1176$ be used at NNLO, brings the Higgs predictions from HERAPDF into much closer agreement with those of MSTW2008.

6 Comparison to early LHC data

Fig. 8 show comparisons of the HERAPDF1.5 NLO predictions to the early LHC data on the W asymmetry from CMS and ATLAS. Predictions from other PDFs show a similar level of agreement. This figure also show comparisons of various PDFs to the ATLAS inclusive jet data. The W data have also been used for very preliminary evaluations of their impact on the PDF uncertainties by both the HERAPDF and the NNPDF groups. NNPDF [23] have used a reweighting technique to assess the impact of these data, finding improvements of the order of $\sim 40\%$ in the u and d -quark. HERAPDF have fitted the asymmetry data from CMS in addition to the inclusive HERA data and the CDF Z^0 and W -asymmetry data. They find a modest improvement for the valence quark densities at low- x - the region that Tevatron data do not reach.

Plots illustrating these improvements and further comparisons of the PDFs to each other

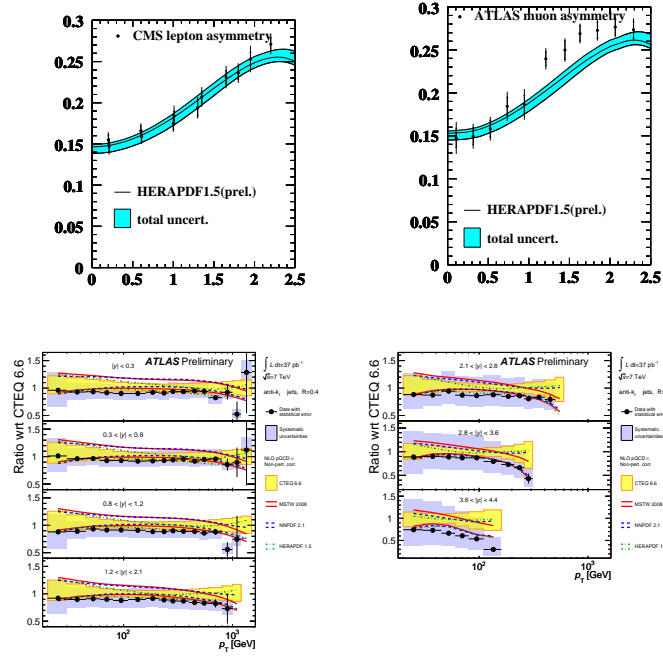


Figure 8: Top: HERAPDF1.5 predictions for LHC W -lepton asymmetry data from CMS and ATLAS data. Bottom: ATLAS jet data in the central and forward regions in ratio to the predictions of CTEQ6.6 and compared to other PDF predictions.

and to Tevatron and early LHC data can be found at

<https://wiki.bnl.gov/conferences/images/1/1a/Plenary.Cooper-Sarkar.0415.talk.pdf>

See also the review of Watt [24] for recent work on benchmarking the PDFs.

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